Linear polarization on Gamma-Ray Bursts: from the prompt to the late afterglow

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Abstract. The past year has witnessed a large increase in our knowledge of the polarization properties of Gamma-Ray Burst (GRB) radiation. In the prompt phase, the measurement (albeit highly debated) of a large degree of linear polarization in GRB 021206 has stimulated a deep theoretical study of polarization from GRB jets. The optical afterglow of GRB 030329, on the other hand, has been followed thoroughly in polarimetric mode, allowing for an unprecedented sampling of its polarization curve. I will review the present status of theories and observations of polarization in GRBs, focusing on how polarimetric observations and their modelling can give us informations on the structure and magnetisation o GRB jets which is not possible to obtain from their light curve.

INTRODUCTION

Linear polarization has revealed to be a characteristics of GRBs throughout their entire evolution. The recent claim by Coburn & Boggs[2] that the prompt emission of GRB 021206 was polarized at a very high level has stimulated a thorough analysis of the polarizing properties of the jet geometries in GRB outflows, drawing attention on the possibility that magnetic fields may be advected from the central source rather than generated by the internal shock. On the other hand, observational and theoretical studies of afterglow polarization has revealed a much more complicated picture than previously thought, emphasising the importance of the jet structure, its dynamics and the properties of the ISM in shaping the polarization curves. Even though direct observations lack, also the optical flash may be highly polarized, especially if due to a reverse shock in the burst ejecta rather than to the pair enrichment of the nearby ISM.

In this paper I review the status of theories and observations of linear polarization in GRBs. The three phases are analysed initially separately and then their relation discussed. The importance and insight of polarization is emphasised in all phases.

THE PROMPT PHASE

Analysing the scattering geometry of photons in the RHESSI detector, Coburn & Boggs [2] were able to measure the average linear polarization of the prompt emission of GRB 021206 in the [150 keV–2 MeV] energy range. They find that the prompt emission of the burst is highly polarized, with $\Pi = 0.8 \pm 0.2$. This measurement was subsequently heavily criticised by Rutledge & Fox [20], who performed an independent analysis of the same dataset, obtaining a much smaller number of double-scattered photons and, as

a consequence, merely an upper limit on the linear polarization of the event. Despite that, the result [2] has stimulated a vast theoretical effort in order to understand under which conditions such a large polarization could be obtained. Two classes of models have emerged. In the first class, the origin of polarization is ascribed to the presence of a large scale ordered magnetic field, which ought to be advected from the central engine and may play a role in the launching of the jet itself [14]. In the second class of models, the magnetic field is supposed to be shock generated and tangled on small timescales, and the asymmetry required to produce polarization is due to a particular location of the observer with respect to the jet axis [22]. This second class of models can be extended to different emission mechanisms, such as inverse bulk Compton scattering [12].

Magnetic models

We define here magnetic models those in which polarization is due to the large scale geometry of the magnetic field. The magnetic field is likely to be dominated by a toroidal component, since the radial field decays faster than the tangential one ($B_r \propto r^{-2}$ while $B_\perp \propto r^{-1}$). One important ingredient of these models is that the observer, due to the relativistic aberration of photons, cannot see the whole jet. In fact it is only a small $1/\Gamma$ region of the jet that is observable and therefore the observer does not detect the overall toroidal structure of the field (which would wash out the polarization signal) but a highly ordered patch. This is most important if the magnetic field is not the dominant component of the outflow. Since regions of the jet separated by more than $1/\Gamma$ are causally disconnected, it is difficult to envisage a coherent magnetic field on scales larger than $1/\Gamma$, unless the structure has been created before the acceleration of the jet (when it was still connected) and frozen into it. Such a transport seem easier to attain in a magnetic dominated outflow [17] and even natural in a force-free subsonic bubble [14].

Even if the observer has access only to a fully ordered region of field, the polarization signal cannot be as large as that expected from a non relativistic flow. In the classic case: $\Pi = (p+1)/(p+7/3)$ where p is the power-law index of the electron energy distribution. The reduction of the observed polarization in the relativistic case is due to the aberration of photon trajectories. In order to keep the electric and magnetic field of the wave orthogonal to each other and to the wave propagation direction, the position angle of polarization is rotated in different ways as a function of the distance from the line of sight. After integration, the polarization is reduced by a factor that depends on the spectral slope of the radiation, and spans between 10% and 20%. The non-relativistic solution is shown with the relativistic maximum polarization in the left panel of Fig: 1 (see also [7]).

A characteristic feature of these models is that any observer located within the opening angle of the fireball detects a highly polarized signal, with the exception of those observing the fireball within $\theta = 1/\Gamma$ from the symmetry axis. A level of polarization comparable to that detected by Coburn & Boggs cannot be achieved, even though given the large uncertainties a definitive conclusion cannot be drawn.

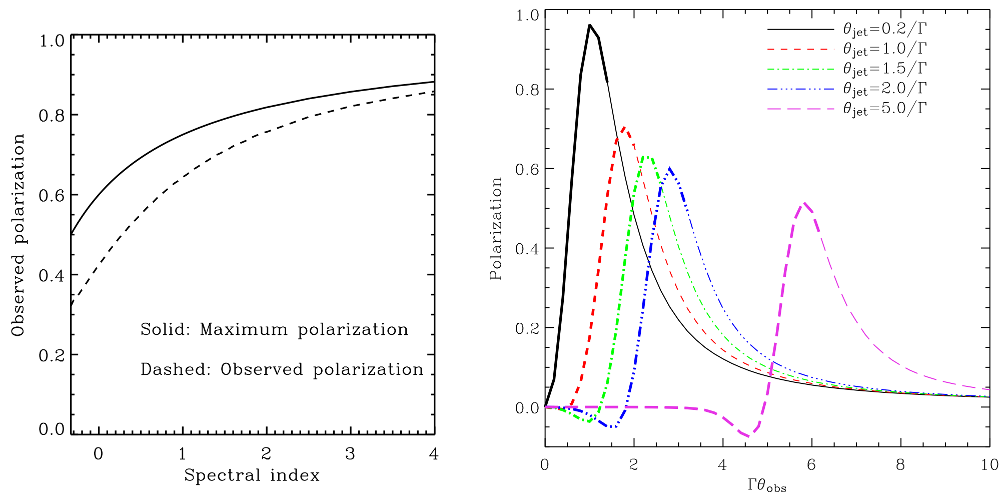

FIGURE 1. Left panel: Maximum synchrotron polarization for a non relativistic uniform field as a function of the spectral index α (solid line) compared to the maximum observable polarization from a relativistically moving uniform field (dashed line). The electron pitch angle distribution is uniform in both cases.. **Right Panel:** Inverse Compton polarization as a function of the observing angle θ_o in units of $1/\Gamma$ for a uniform jet with sharp edges. Different line styles show the polarization for jets with different opening angles. The lines are thicker in the region where the efficiency is larger than 2.5%.

Geometric models

It has been traditionally assumed that the magnetic field responsible for the synchrotron emission in GRBs is generated at the shock front. This is a robust conclusion in the afterglow phase, where the compression of the interstellar field is far too low to produce the observed radiation. It may hold true also for the prompt phase, in which case a tangled field would be responsible for the observed radiation. If this field is tangled in a plane, but compressed in the direction perpendicular to the plane itself [11, 15] it is possible to observe polarized synchrotron radiation since radiation emitted in the plane, which is maximally polarized in the comoving frame, is then aberrated toward the observer with an angle $\theta = 1/\Gamma$ [5].

In the afterglow phase, this configuration leads to polarization of up to several tens of per cent [5, 21], but in the prompt phase is usually negligible, unless a narrow jet is observed along the required direction [22]. Polarization in this context has been analyzed in several works with synchrotron as the radiation mechanism [7, 16] as well as if the photons are produced by bulk inverse Compton scattering [12]. The difference between the two cases is not of fundamental nature, since the dependence of polarization on angle is the same for the two mechanisms. Inverse Compton, on the other hand, can produce larger polarization since it can be maximally (100%) polarized in the comoving frame.

The polarization produced by a narrow jet is shown (for the case of inverse Compton) in the right panel of Fig. 1. In these models a narrow jet is fundamental since the number of observer that see a polarized event is limited to those lying in the region between the edge of the jet and $1/\Gamma$ from it. This region becomes vanishingly small for $\theta_{\rm jet} > 10/\Gamma$. GRB 021206 was exceptionally bright and, assuming it was at cosmological redshift,

would have had a narrow jet with opening angle of few degrees at most.

To distinguish between magnetic and geometric models is quite easy once a reasonable number of measurement is available. In the geometric case only a small fraction of the brightest bursts should be polarized, while in the magnetic case most of them should.

THE FLASH

It has been suggested by Granot & Königl [8] that the reverse shock emission could be as highly polarized as the prompt GRB, since the plasma responsible for this emission is the same one that produced the gamma-ray photons. This consideration can be included in a more general discussion on optical flashes, i.e. bright optical components that appears at the beginning of the afterglow phase with a fast decay.

Optical flashes can be produced in two ways: by a reverse shock in a baryonic jet or by pair enrichment of the external medium in the vicinity of the GRB [1]. In most cases the optical flash is expected to be polarized at a level comparable to the prompt emission. There is actually only one case in which the optical flash following a polarized GRB can be unpolarized. In a magnetic model, if the flash is due to pair enrichment of the ISM, the flash comes from a shock generated field without the geometric constraints to produce polarization. In all geometric models the geometry of the prompt phase is preserved during the flash emission. Finally, if the flash is due to reverse shock, it should be polarized as discussed by Granot & Königl [8].

AFTERGLOW

The discovery of linear polarization in GRB afterglows dates back to 1999, when a small but highly significant level of polarization was detected in GRB 990510 [3]. The detection took place amid a theoretical effort to predict and/or explain it.

Guzinov & Waxman [10] discussed the possibility that the shock generated field organises in coherent patches that expand at a sizable fraction of the speed of light. They calculated that an observer should see approximatively $N \gtrsim 50$ patches. If the polarization inside a patch is $\Pi_0 \sim 70\%$, the observed one is $\Pi = \Pi_0/\sqrt{N} \lesssim 10\%$. Indeed the degree of linear polarization observed in GRB afterglows is in the per cent range (see [4] for a review). However, given the random nature of the model, the degree and position angle of polarization fluctuates in time. This is not, at least in some cases, detected in polarization curves [13, 9] and for this reason this model is now not considered particularly promising.

Shortly after the discovery of polarization Ghisellini & Lazzati [5] and, independently, Sari [21] proposed a model based on the assumption that the fireball is beamed in a come and that the shock generated field is either compressed in the shock plane or elongated in the axial direction. Polarization is observed if the observer is not coincident with the cone axis and has a definite and testable pattern. Polarization at early times is null, increases slowly with time until it reaches a maximum and then starts to decrease again until it vanishes. At this moment, which is roughly coincident with the jet break in

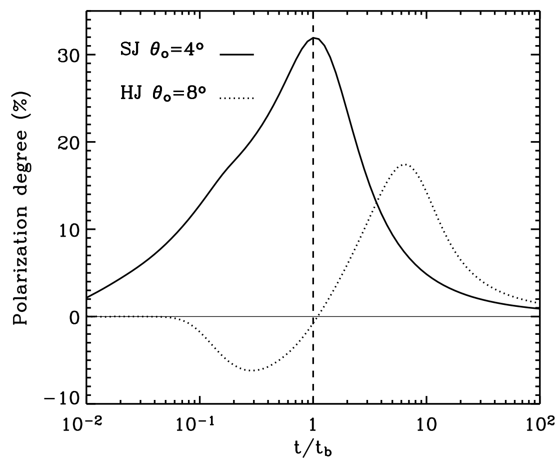

FIGURE 2. Comparison between the polarization curves of a homogeneous jet (dotted line) and a structured jet (solid line). The two light curves are virtually indistinguishable, while polarization behaves in a markedly different way.

the unpolarized lightcurve, the position axis of polarization rotates by 90°. Then the polarization curve is characterised by a second peak, of higher intensity, eventually vanishing to an unpolarized flux at long times. The intensity of the polarization signal depends on the off-axis angle: the larger the off-axis angle the larger the polarization.

These models have been further analyzed and extended by Rossi et al. [19]. They studied the effect of different assumptions on the jet sideways expansion showing that the ratio between the peaks of polarization is smaller for faster expansion speed. They also generalised the model to non uniform jets, in which the energy per unit solid angle decreases as $E_\Omega \propto \theta^{-2}$ where θ is the angle with respect to the flow symmetry axis. In this case the polarization curve is largely different. While it is null for early and late times, as in the uniform case, it has a single peak, correspondent in time with the jet break time, and constant position angle. In Fig 2 we show the comparison between the polarization curves for the homogeneous and the structured models. It is clear that the two curves are different in an easily testable way. This is particularly important if we consider that the light curves of the two models are almost indistinguishable. Further complications to the models have been added by [8] who consider the presence of a coherent component of the magnetic field in the ISM. The propagation of the polarized light of the OT in the host and Galactic ISM have been instead discussed by [13].

Comparison of the models with the data has proven difficult. The main limitation of these models is that they assume that the emissivity of the fireball is uniform (or strictly dictated by the θ^{-2} law). Any deviation from this assumption, or inhomogeneity of the external medium, causes a noise on top of the models in both< polarization and position angle. Usually this situation is recognisable in the light curve through the presence of bumps and wiggles on top of the regular power-law decay. Indeed, every time the light curve is complex, the polarization curve has a complex structure, such as in GRB 021004 [18, 13] and in GRB 030329 [9]. On the other hand, simple polarization curves seem to be associated to power-law afterglows (GRB020813 [6]).

COMPARISON OF THE THREE PHASES

The position angle of polarization should be related in the three phases. In the intrinsic models (i.e. neglecting polarization induced by the ISM and by an external magnetic field) the position angle of the polarization can be either contained in or orthogonal to the plane containing the jet axis and the line of sight. It is therefore expected that, should polarization be measured in the future in the three phases of a single GRB event, the position angle should either remain constant throughout the whole evolution or rotate by 90° between the optical flash and afterglow. It may eventually rotate back to the original position. Any difference from this simple behaviour should be considered a sign of an external component in the generation of polarization.

SUMMARY AND CONCLUSIONS

The study of polarization evolution in GRBs is highly informative, albeit difficult. It carries important informations about the jet structure and dynamics that are hidden in degeneracies of the light curve, but are emphasised in the polarization curve. Observationally, the afterglow phase is the most simple to investigate, even though is may be affected by small-scale inhomogeneities, and constraining the smoothness of the light curve is of fundamental importance in order to model a polarization curve. Polarization in the prompt and optical flash emission is highly informative of the structure of the ejecta, even though further observations are required in order to establish the mere existence of polarization in this phases.

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